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The Multidisciplinary Engineer in the Context of Concurrent Engineering

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Throughout the evolution of the design of flight vehicles, the role of the individual engineer has also evolved. As aircraft have become more complex and performance envelopes have become ever larger, the role of the technical specialist has diminished in favor of the design team approach. Although the theme of the symposium deals with aerodynamic design and optimization, many comments apply to all technical disciplines. In this paper we review this design evolution very briefly. It is suggested that the evolutionary design process led to independent technical disciplines, technology development along the same lines and finally engineering education in the same engineering sciences. Concurrent engineering is discussed, together with the advantages and disadvantages from the viewpoint of the practicing engineers. It is suggested that the required approach leads to a requirement for engineers with a broader view than the traditional specialists. Next we consider the education process which, for design engineers, has evolved from apprenticeship to curricula that teach the engineering sciences. It is suggested that we may need to consider moving to the science of engineering. Finally, a possible view of future aerospace vehicle design is presented.

Introduction

The Air Force Research Laboratory does not design aerospace vehicles, per se, so the sense of our work is more from the aspect of analytical or conceptual design to analyze the impact of new technologies. The individual technologies mirror the ones considered in aircraft design, so that the same comments apply and are used interchangeably in this paper. In the Laboratory context, it is just as important to be able to demonstrate the potential benefit of a proposed technology if it were integrated into a system. In prioritizing technologies, whether in a design or a laboratory development, there is always the question of what is more important to the customer. Thus there is a need for a design and analysis capability, although not to the same level of detail as for a project to be built. There are similar pressures to use concurrent engineering practices and arrive at a valid interdisciplinary result. In fact, it is to be expected that many papers in this symposium will contain similar themes.

In the "old-fashioned" traditional design, many of the technical disciplines could be and were pursued in an independent or serial way. There are a variety of factors that have changed that simple view of aircraft design, and continue to change the design process at an ever-increasing rate. Aircraft are becoming more and more integrated, so this means that the traditional ways became less and less efficient. At the same time, the traditional pursuit of performance increases has given way to a strong emphasis on affordability, safety, environmental impact and information technology, etc. There have been a number of studies of the acquisition process within the US Department of Defense. The results have unanimously shown the need for drastic changes in the way major weapon systems are developed and acquired, but the relevant aspects for this paper are the design aspects. The need exists for new design concepts to be analyzed in great detail in the context of operational use in order to demonstrate benefits and uncover problems as early as possible. We should even take a fresh look at the mechanisms and strategies for optimizing aerospace vehicles, since the optimization constraints are also evolving. From the original requirements for basic stability and controllability, there was a period in time when increases in maximum speed were the primary focus. Then the focus became maneuverability for fighter aircraft. Now the primary focus is shifting away from performance aspects, and affordability is of equal or greater importance.

The foregoing discussion is only a very brief indication of the changes in the aircraft design process which have occurred and will continue. As the requirements change, such as the increasing importance of affordability rather than pure performance, the tools for designing, or even analyzing, systems with such constraints may not exist. The historical interactions may also change because of advancing technology, so that the historical data bases may need re-interpreting. As an example, aircraft cost models are predominantly based on weight and it is common to hear that we buy airplanes by the pound (or kilogram). Many factors are implicit in those correlations, however, that are part of the manufacturing process for the historical metal airframes. Thus the cost models are accurate for metal aircraft that are manufactured the same

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way that the previous ones were. The actual models do not represent the "physics" of manufacturing an airframe, especially as we progress more and more towards use of composite materials with different detailed activities. With all of the changes, engineers need to be less specialized and more and more cognizant of related technical disciplines. It is important to understand the questions before working on the answers.

The theme of the symposium is "Aerodynamic Design and Optimization of Flight Vehicles ..." but many comments apply to the other disciplines with equal validity. The focus of the paper is that we can no longer afford to optimize any one particular discipline because that guarantees a suboptimum system. A more appropriate theme might be "The Role of Aerodynamic Design in System Optimization". The concurrent engineering process is discussed with some contrast to historical methods, followed by discussion of the implementation through Integrated Product Teams. Specific activities at the Air Vehicles Directorate of the AFRL are presented, including the creation this year of a Center for Multidisciplinary Technology which is tasked with addressing these issues. Some comments are presented relative to educating the new breed of engineers suggesting that we move forward from just teaching the engineering sciences towards the science of engineering. Lastly, there is a discussion of a possible future of vehicle design, although not as a forecast, but as a "vision of things that might come". Throughout this paper, examples are drawn from many sources, including the author's personal experiences in order to illustrate or prove various points.

Concurrent Design Processes

First, it is convenient to discuss the concurrent design environment that is the theme for both the symposium and this paper. We can consider the process for a new airplane system today, and contrast it with past practice. The concurrent design process relies on some form of systems analysis, or systems engineering. This has been expressed as:

1. Break the system under consideration down into component parts.
2. Gain an understanding of each individual part.
3. Determine how these parts interact.
4. Define the contribution of each component to the system performance
5. Put the system back together again.
6. Build it when the analysis shows that the design meets requirements.

At the risk of over simplifying the discussion, the old fashioned methods developed a reasonably good process for steps 1 and 2. It was not uncommon, however, to minimize the effort on steps 3 and 4 and then move on to step 5 and build a prototype and fly it to see if it met requirements. In the "good old days" it was possible to build competing prototypes and choose the one that met requirements the best, rather than the analysis of step 6. The definition of the individual parts came early in the development of aircraft design. In this context, for instance, the aerodynamicist was responsible for predicting lift and drag and calculating mission performance (cruise speed and range, plus field length). History is replete with examples of the pitfalls of component optimization which yielded overall system sub-optimization. The original Spitfire wing was a perfect elliptical planform which minimized induced drag, i.e. optimized the wing performance. In combat it was soon learned that roll performance needed improvement, and the outer wing planform was cropped in later versions. The optimum wing for induced drag generated too much roll damping so that the total aircraft was not optimized for its primary mission.

In that example we see the negative aspect of the success achieved in breaking the system under consideration down into component parts. It led to the disciplines of aerodynamics, structures, controls and subsystems being defined, understood and analyzed as the essential components of an airframe. Each discipline could be studied, developed and analyzed separately. In the university setting these were taught as individual engineering sciences. In a project setting separate design groups were responsible for the same disciplines. Lastly, in the Laboratory setting, this approach led to those disciplines becoming individual technology empires.

Obviously, the disciplines were never completely independent of each other. In any real aircraft design project, connections and interactions between the individual disciplines that had to be considered were defined as in step 3. For example, 'the aerodynamics group' calculated loads for 'the structures group' to use in their design; 'the aerodynamics group' calculated control effectiveness and hinge moments for the 'the controls group' to use; etc. It is suggested, however, that it is not a gross exaggeration to claim that these interactions were often not really integrated. It is often referred to, facetiously, as passing your results over the partition to the other group. A significant area of research today is devoted to modelling such interactions, including the vision of complete physics-based models that can be used for the purposes of aerospace vehicle analysis and design.

Step 4 is one area that is still showing continual improvement in capability. Today it is common to simulate the predicted performance during the design development so that the above Spitfire problem and similar problems are avoided. In order to counteract such problems, we "apply knowledge earlier" to the extent that the future use can be predicted. As aircraft systems become more and more complex, we are faced with more and more integration with non-traditional technical disciplines. An aerodynamicist today may be tasked with designing control surfaces that are integrated with thrust vectoring to produce the required total aircraft performance and response. Until recently, the powerplant for conventional aircraft was largely developed independently. "Integration" was mostly a definition of the interfaces. Even for V/STOL aircraft, thrust vectoring and reaction controls were only used as the aerodynamic controls lost effectiveness due to the reduced airspeeds. The design issue could be considered more of a blending than a true integration of effects.

A really critical part of the process is step 6. It seems deceptively simple and straightforward – analyze the system to show that the design meets the requirements. What analysis ? Because the wrong analysis, no matter how rigorous, will give the wrong answer (at least the vast majority of the time). Alternatively, how often is the answer "known" before the analysis is done to prove it ? How much analysis is enough, i.e. can we quantify a confidence level ? I will claim that we cannot perform analyses today to show with 100% confidence that a design meets all requirements. A design trade space may also exhibit local minima or optima that can guide an incomplete analysis to suggest something less than the global optimum. In addition, it may be more productive to show sensitivities or trade-offs between design options and some of the requirements. In order to accomplish that, however, we need to consider at which point in the 6-step process that should be done. This question leads to discussion of step 5.

Step 5, "put the system back together again", can be done on various levels. For a point design, a process of linear superposition may be adequate to define the primary contributions of the components. In order to perform trade-offs, however, the interactions between the components needs to be modelled. The higher the order and fidelity of that modelling, then the more credible the results will be. The extreme solution, for the very distant future, is to use physics-based calculations and generate a completely faithful design matrix of every design parameter vs the complete range of outputs. But these outputs will range from maximum speed to maintenance manhours. Then we can trade off an aerodynamic feature against life cycle cost. This will be discussed later.

Integrated Product Development

An aspect of system or concurrent engineering that has found its way into many projects today is known by different forms of the phrase: Integrated Product Team (IPT). In practice, it varies from a true interdisciplinary team to address a specific problem to the extreme of just the formation of an IPT is the management solution to any problem. The real intent is to assemble the appropriate team to work on specific interdisciplinary problems, such as the design of an integrated flight/propulsion control system. The appropriate team consists of the personnel responsible for designing any portion of the system together with those affected by performance of the system. In this example from the author's experience (see Kisslinger and Moorhouse), the team represented the different contractor functional areas, all the major subcontractors and different Government agencies. The Interface Control Sheets had been defined in one-on-one meetings between the Contractor and the various Suppliers. In any complex system, however, there are likely to be indirect effects of one component on some other, apparently unrelated, component or function. For this to happen, it means that there was incomplete knowledge relative to step 3 above. The rationale was to anticipate and address integration questions as early as possible, and also to involve all the Subcontractors and Subsystem Managers in the discussions, so as to uncover any possible indirect effects as early in the development process as possible.

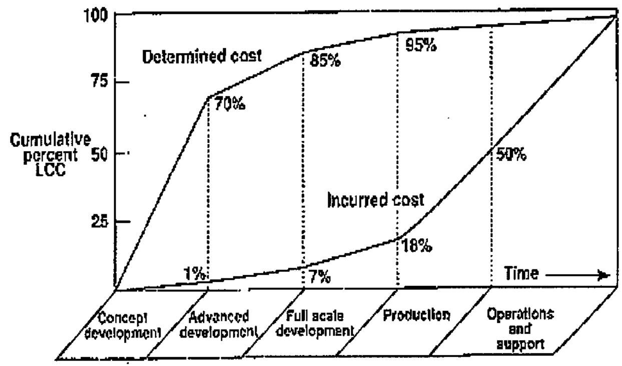

Figure 1. The Life Cycle Cost Problem

Another aspect that is receiving much attention is the timing of program decisions. It has been shown that the majority of an acquisition program's costs are essentially decided very early in the project design, see Figure 1. It is believed that this happens because many decisions are made before the knowledge to support such a decision has been obtained. It is also true, in many cases, that many costs were driven by inflated requirements. It has been tempting to ask for more than necessary "just in case", but this is also evidence of the lack of the right knowledge. The answer to the problem is to bring that downstream knowledge forward in the design process, as depicted in Figure 2. Although this seems like a contradiction, it is being implemented in many initiatives such as the US Department of Defense's Simulation Based Acquisition, NASA's Intelligent Synthesis Environment, and others. The basis of all these efforts is computational simulation and modelling, which relies on high-fidelity models of the total system. Once again, the basis is interdisciplinary or multidisciplinary analyses rather than a concentration on any one discipline, or even a limited sub-set of disciplines. Again the ideal is for a group of engineers to address the problem where the team knowledge has to exceed the sum of the individuals, i.e. concurrent engineering.

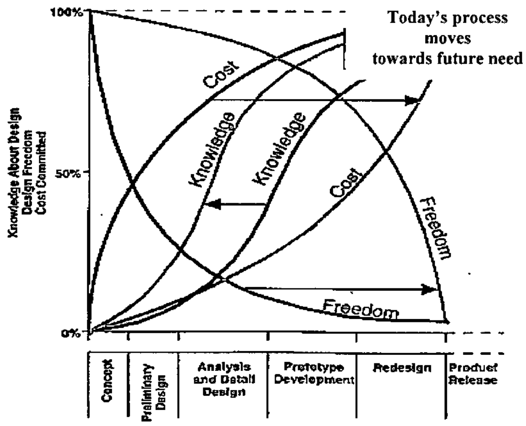

Figure 2. The Design Process Paradigm Shift

The Air Vehicles Approach

In the AFRL Air Vehicles Directorate, aerodynamic design and optimization is evidenced in a Center of Excellence for Computational Simulation. From its start in Computational Fluid Dynamics, i.e. the pure science of aerodynamics, the Center is now addressing various technical couplings such as the effects of structural modes on the aerodynamics. There is another drive to develop solutions for Maxwell's equation in addition to Navier-Stokes equations in Computational Electro-Magnetics. This computational center is also linked to a Center for Multidisciplinary Technologies. We are developing the physics-based models for an ever broadening range of technical disciplines. The ultimate goal has to be the creation of the capability to analyze, synthesize, design and optimize the complete aerospace vehicle.

Earlier this year (1999), the Directorate created a new Center for Multidisciplinary Technology. The Center was chartered to "invent and develop new and improved theories, processes and tools, using them to enable revolutionary vehicle concepts". It covers the range from basic research into the development of new and innovative optimization algorithms through to applied research into higher-order integration and development of technologies. The charter includes:

- Energy-based constraints
- Non-linear theories
- Cost-based optimization
- Synergistic interactions
- Futuristic integration
- Configuration inventions

A key component of the center is a technology application group, whose operation and activities are subject to all the constraints discussed above. This group is responsible for developing or acquiring the capability to perform the vehicle concept assessments, and support technology development from a total system aspect. It is also responsible for providing the links to two other Centers of Excellence. In this way, the basic technical disciplines of aeronautical sciences, control systems and structures can be assessed in an integrated fashion. Obviously, we are also faced with incorporating models of other disciplines, such as propulsion, in order to have a credible assessment. In DoD nomenclature Air Vehicles technologies plus Propulsion technologies add up to Air Platform technologies and all programs are subject to high-level review from that perspective.

As the Center looks into the future, the requirements to adhere to the concurrent processes will become mandatory. A vision of basing aerospace vehicle design on natural principles, see figure 3, will probably seem unnatural at first sight. It is based on an assertion that natural selection is a process of discovery through experimentation. In nature, if something is inefficient then it dies out. In the aerospace vehicle context, therefore, there is a need for better tools and processes for discovery through desining for maximum efficiency and minimum energy waste. This approach will require:

- High-order computational modelling
- High-level design tools
- Energy-based natural selection

The ultimate promise is to be able to realize a fully-integrated and fully-optimized vehicle design.

<u>**PAST**</u>: Discovery Through Experimentation
Also Nature's Process of Selection

<u>**NEED**</u>: Common Metric for Every Aspect ~ Energy ??
Maximum Efficiency/Minimum Energy Waste

<u>**FUTURE**</u>: **Numerical Experimentation** Using
* High-Level Design Tools
* High-Order Computational Modeling
* Energy-Based Natural Selection
* Fully-Integrated & Optimized Vehicle Design

Figure 3. Design Based on Natural Selection

In order to include all relevant technical interactions, we should probably start off by assuming that **all** interactions are relevant. The greatest barrier to achieving a successful result is accepting something as a given without question. In fact, if we refer back to Figure 2, the real problem may be that the practitioners start off the process with a set of assumptions and do not realize that they are starting off with zero knowledge. It may also be instructive to consider a variety of lines on Figure 2, e.g. assumed knowledge vs actual knowledge, program management knowledge vs engineering knowledge, etc.

Engineering Education

Based on the preceding discussion, we can consider what aspects of engineering education may require changes in order to be aligned with the needs of a multidisciplinary engineer in a concurrent design environment. The embodiment of today's reality can be seen in the stated goal of NASA's new Intelligent Synthesis Environment initiative: "To develop the capability for scientists and engineers to work together in a virtual environment, using simulation to model the complete life cycle of a product/mission before commitments are made to produce physical products". Notice also that this very ambitious statement also promulgates the tradition that engineers and scientists are distinct. Universities were founded to "teach learning, i.e. science". Engineers who built things learned their trade as apprentices. As time passed, universities taught the engineering sciences but not the science of engineering, in this author's opinion. The old-fashioned traditions were continued, however, in that when the young engineer began employment in "the real world" he was typically assigned to a senior engineer and trained on the job. The expectation was that a new graduate (at whatever level) did need training in the "real aspects of the job or project".

Universities today are becoming more involved in teaching what the aerospace industry really needs, i.e. graduates with some experience in working in a team environment on a multi-dimensional problem. In the USA, in this author's opinion, the Georgia Institute of Technology in Atlanta, Georgia, is the most advanced in offering graduate degrees in aerospace vehicle design. The philosophy has been expressed as producing a "T-shaped engineer" i.e. the student is taught a broad range of engineering subjects to a certain level of detail, plus at least one specialty subject in depth. As a purely personal opinion, I consider that I got a very good undergraduate training in the broad range of subjects required to receive a degree in mechanical engineering. I suggest that the real difference is that the engineering subjects need to be taught, not as separate engineering sciences, but linked together in the interdisciplinary nature of real world problems. The linking together of the engineering sciences to provide multidisciplinary understanding is what forms the top of the "T" in shaping an engineer, this is the science of engineering. This concept is depicted (humorously) in Figure 4. In order to accomplish this, graduate students are assigned to work on team projects. At Georgia Tech, this is accomplished through an Aerospace Systems Design Laboratory. Students are assigned design projects and use state-of-the-art computer programs, many of which are advanced by the doctoral thesis work. In addition, there has been a relatively recent trend for professional technical societies and organizations to encourage such team projects. A visible sign of these activities is the various "build and fly" competitions that are held as university challenges.

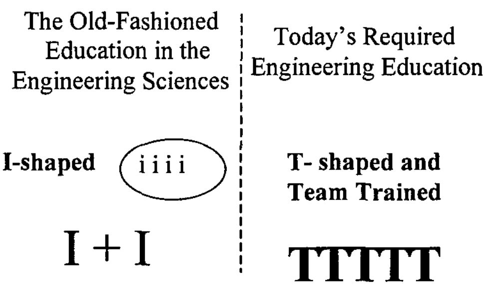

Figure 4. Education for Concurrent Engineering

The Future

Part of this discussion may also be considered as learning from history. It is known that the Wright Brothers studied birds as they were solving the basics of controlled flight, and the same is probably true of most of their contemporaries. Wing warping as a roll control device certainly came from the Wrights' observation of the aerodynamic shape of bird's wings in flight. This author has not seen any explanation for the design of the aileron that soon replaced wing warping for roll control. We know, however, that wings structures were made stiffer as speed and maneuvering increased. Very soon after those early flights aircraft design engineering became an evolutionary process of development from the preceding model. At AFRL today, however, wing warping is being researched again in the Advanced Aeroelastic Wing (AAW) program. So, is the aerospace vehicle design community at a point where we can learn again from nature in order to make the next major advance ?

The theoretical base is being developed that will allow the application of energy-based principles to aircraft design (Bejan 1997). It is a logical process to consider static systems such as power or refrigeration plants in terms of an energy balance, in order to analyze and minimize the losses. The same principle is being applied to aircraft systems (Bejan 1999). That work is a discussion of "new opportunities for thermodynamic optimization" including the thermodynamic optimization of flight.

In a simple one-dimensional view, the aerodynamic optimization to reduce drag is already an example of minimizing the use of energy represented by fuel burned. We can write a balance of the fuel burned by the engine in order to do work overcoming the drag of the airframe. This is the implicit consideration of the traditional performance analysis, although it has been typically used to calculate the range or radius with specified mission constraints. This traditional analysis has been based on very simple models of an airplane that was designed through trial and error processes rather than a true integrated procedure. The engine also has to supply energy, in different forms, to drive the hydraulic pumps, to power the environmental control system, etc. The power that is required from the engine for these functions is not calculated on a real-time basis and is usually a simple average, so the analysis of a mission that includes combat maneuvering is only an approximation, at best. Further, that environmental control system has probably been designed as an independent subsystem and "integrated" via the definition of the interfaces.

Now, if we look into the future and consider the design of a total aircraft system in terms of an optimum balance of energy then all the classical engineering disciplines must be re-assessed. The first consideration is whether the engineering tasks can all be formulated in a common framework of energy or thermo-economic metrics. The answers to this question probably range from the trivial to the very complex. It is in vogue currently to claim optimization of life cycle cost, which is impossible to calculate with any degree of certainty using the available models. If we consider the potential of using energy-based optimization, then "everything" must be put in thermo-economic terms but to do this we must consider energy and cost to be equivalent units. The future of this methodology depends on being able to formulate the individual technical disciplines in this common framework for analysis and optimization, in parallel with the development of the necessary physics-based modelling.

Conclusions

A century of manned flight has been summarized in the briefest way possible to consider the role of the technical specialist, such as the aerodynamicist, in the modern design context. It is suggested that the time has already passed when the individual technical disciplines could be practiced independently. Optimization of individual disciplines leads to a sub-optimum system. This is probably obvious to many when considering design of a flight vehicle, but it is also just as true when considering applied research and technology development. Now, and for the future, each technical discipline has to be considered in a multidisciplinary environment to satisfy the object of concurrent engineering. The theme of the symposium might be stated as "The Role of Aerodynamic Design in System Optimization".

The required education for "modern engineers" was discussed. No matter how good an engineering education was, it seldom prepared the graduate for the realities of a design team. I suggest that the next generation of engineers should be trained in the science of engineering rather than continue with separate treatments of the engineering sciences.

The original flight experimenters did study nature, and especially birds in flight. Aircraft design, however, soon became an evolutionary process. The question is posed: can we may new technology leaps by a return to nature? Further, nature is suggested as a minimum energy waste design constraint. For the future, maybe the emerging discipline of thermo-economics can be developed as a methodology for total vehicle system optimization. The AVT Panel might also consider that such an energy-based design methodology would be equally applicable to ships and land vehicles as well as aircraft.

Finally, within AVT are the technical disciplines of aerodynamics, structures and propulsion, i.e. three of the traditional technical disciplines. There needs to be integration with other RTO Panels in order to realize the full potential of a fully integrated concurrent engineering design process.

References

Bejan, A., "Advanced Engineering Thermodynamics", second edition, Wiley, New York, 1997.

Bejan, A., "A Role for Exergy Analysis and Optimization in Aircraft Energy-System Design", Proceedings of the ASME Advanced Energy Systems Division – 1999, S. Aceves, ed., ASME, New York, 1999.

Kisslinger, R. L., and D. J. Moorhouse, "Lessons Learned in Control System Integration & Management from the S/MTD Program", Society of Automotive Engineers Paper 901849, SAE Aerotech '90, October 1990.

DISCUSSION

Keynote Session, Paper #3

Dr Render (Loughborough University, UK) queried the applicability of "T-shaped engineers" to specialist tasks, particularly the production of the tools required by the multi-disciplinary engineers.

> **Dr Moorehouse's** ideal was that tools would be produced by "T-shaped engineers" with a specialty in computer science. He felt that engineers might write inefficient code, but code which would produce the correct answers. He expressed little confidence in tools written by computer specialists with no engineering knowledge. He suggested an IPT (Integrated Product Team) approach to capture the required engineering and computer skills.

Mr Woodford (DERA, UK) sought clarity on the distinction between "acquisition" and "production" costs. He also asked the author for his views on the establishment of cost as an independent technical discipline.

> **Dr Moorehouse** noted that his charts should have referred to three distinct components of life cycle cost, i.e. "development", "manufacturing" and "operations and support". He agreed that cost should be considered as a technical discipline subject to the same demands for fidelity and rules of optimization. He noted that cost is not an independent variable and should be taught and considered as a component of a multidisciplinary process.